EXPERIMENTAL OF TAILOR WELDED BLANKS FABRICATED USING FRICTION STIR WELDING (FSW)

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DECLARATION

I hereby declare that the project thesis entitled "EXPERIMENTAL EVALUATION OF TAILOR WELDED BLANKS FABRICATED USING FRICTION STIR WELDING (FSW)" submitted to School of Mechanical Engineering, Universiti Sains Malaysia; ADHA FAHMI BIN PAUZI in partial fulfilment of the requirement of Bachelor of Degree in MANUFACTURING ENGINEERING WITH MANAGEMENT is a project carried out by me under the guidance of Assoc. Prof. Ir. Dr. Ahmad Baharuddin bin Abdullah.

I further declare that the work reported in this project has not been submitted and will not be submitted, either in part or in full, for the award of any other degree or diploma in this institute or any other institute or university.

This article is the result of my own investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

Signed ………………………………………………………………………….

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This thesis has been submitted as partial fulfilment of the requirement for the final year project to the respective academic supervisor.

Signed ………………………………………………………………………….

(ASSOC. PROF. IR. DR. AHMAD BAHARUDDIN BIN ABDULLAH)

Date ………………………………………

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Abstrak

Kimpalan kacau geseran (FSW) adalah proses penyambungan yang agak baru dan telah menghasilkan kesan yang besar terhadap beberapa industri kerana banyak kelebihan berbanding proses kimpalan tradisional. Projek ini bertujuan menyiasat kelayakan kimpalan dua keping aluminium (AA 6061) denganketebalan 3mm oleh proses FSW. Objektif utama penyelidikan ini adalah untuk mengkaji kesan kekuatan tegangan, kekerasan dan kekasaran yang berkaitan dengan kadar suapan (kelajuan kimpalan), kelajuan gelendong (kelajuan putaran), dan sudut mata alat juga untuk menentukan parameter yang paling optimum untuk FSW. Tiga tahap laju suapan iaitu pada 31, 65, dan 90 (mm / min), kelajuan gelendong pada 600, 865, dan 1140 (rpm) dan sudut mata alat di 2, 3, 4 (°) telah digunakan dalam eksperimen. Lekapan pengapit yang ditetapkan pada mesin penggilingan konvensional telah direka bentuk dan dibina untuk membolehkan kimpalan ini. Alat-alat FSW direka bentuk dan dibina daripada alat keluli. Dalam kajian ini, kekuatan tegangan, kekerasan dan kekasaran FSW dioptimumkan menggunakan eksperimen ortogonal Taguchi L9. Ujian tegangan dan kekerasan dijalankan untuk menentukan sifat mekanikal ujian kimpalan dan kekasaran dilakukan untuk menentukan kekasaran permukaan kimpal. Corak kekerasan didapati paling rendah di tengah zon kimpalan. Kedalaman bahu mata alat memainkan peranan pada kekasaran permukaan. Optimum parameter proses telah ditentukan dengan merujuk kepada DoE yang dilakukan. Kadar gelendong dan laju suapan adalah parameter yang paling ketara mempengaruhi kekuatan tegangan kimpal.

Abstract

Friction stir welding (FSW) is a relatively new joining process and has produced a big impact on several industries due to many advantages over traditional welding process. The present works aims investigate the feasibility of welding two pieces of aluminum alloy (AA 6061) sheets of thickness 3mm by FSW process. This main objective of this research is to study the effect on tensile strength, hardness and roughness with respect to feed rate (welding speed), spindle speed (rotation speed), and tool angle and to optimize the FSW parameters. Three level of feed rate i.e. at 31, 65, and 90 (mm/min), spindle speed at 600, 865, and 1140 (rpm) and tool angle at 2, 3, 4 (°) were used in the experiment. The fixture clamp fixed on the conventional milling machine has been design and fabricate to enable this welding. FSW tools were designed and fabricated from tool steel. In this study, tensile strength, hardness and roughness of FSW is optimized using Taguchi L9 orthogonal design of experiments. The tensile and hardness test were conducted to determine the mechanical properties of the weld and roughness test were carried out to determine the surface roughness of the weld. The hardness pattern was found to the lowest at the centre of the weld zone. The tool shoulder depth plays the role on surface roughness. The optimum process parameters were determined with reference to DoE performed. The spindle speed and feed rate are the most significant parameters to the tensile strength of the weld.

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CHAPTER 1

INTRODUCTION

1.0 Overview

This chapter discusses on the project background, problem statement, research objective and scope of the research work.

1.1 Project Background

Tailor welded blanks (TWBs) is the result of joining sheet metal plates with the same or different thicknesses or strengths to produce a single blank prior to the forming test. TWBs technology can give an important possibility to obtain components in automobile industry satisfying lightweight strategies. TWBs can improve crash performance of the auto body. In TWBs, waste become lesser because thinner materials are use. The advantages of TWBs is can reduce the cost by requiring less forming dies. This method also can reduce weight by welding sheet materials with different thicknesses or strength and can meet performance requirement[1]. Part dimensional consistency also can be improved by removing inaccurate spot welding process.

Friction stir welding (FSW), was invented and patented by W. M Thomas et al. of the Welding Institute in Cambridge, UK. In FSW, a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together. The pieces are rigidly clamped onto a backing plate in a manner that prevents the abutting joint faces from being forced apart. Frictional heat is generated between the tool shoulder and the material of the work pieces. This heat causes the latter to reach a viscos-plastic state that allows traversing of the tool along the weld line. The plasticized material is transferred from the leading edge of the tools to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile. It leaves a solid phase bond between the two pieces.

Usually the laser welding or fusion welding method is commonly used in the production of TWBs in steel, but rarely used in aluminium. This is because of the high reflectivity of this material and the presence of layers of refractory oxides. Chemical composition modification, even hot cracking for some aluminium alloys are susceptibility to the formation of porosity in the melted area[1]. Aluminium are invariably less weldable than automotive sheet steels due to high diffusivity and the presence of passive oxide layers, which have a significantly higher melting temperature than the based alloy and often a poorer electrical conductivity. In TWBs, a good weld is crack free and high strength and reliability. The size and shape of the weld pool with low increase in harness is desirable. This project is basically about to evaluate the tailor welded blanks using friction stir welding. Tensile test, hardness test and surface roughness machine were used in the evaluation of the welded strip.

1.2 Problem Statement

Recently, the fusion welding is being used to join the non-ferrous materials such as aluminium in production of tailor welded blank (TWBs). Now days, aluminium has been widely used for automotive industries to make the vehicle weight lighter. Application of friction stir welding is relatively new and the performance of welded blank in term of strength, hardness and quality of the produced surface need to be evaluate and optimize.

1.3 Research Objectives

The general objective of this project is

1. To study the effect of friction stir welding parameter to the strength, hardness and surface quality of the welded blank.
2. To optimize the friction stir welding parameters.

1.4 Scope of Research Work

In this project, friction stir welding was performed on conventional milling machine. To hold the specimen for welding, a special jig was fabricated. There are various parameters that may affect the quality and performance of the welded strip. In this work, three parameters were studied. The parameters are feed rate, spindle speed and tool angle. The basic of parameter selection is mostly based on simplicity on how parameter can be conducted and available facility. Note that this is the first time this type of project conducted in the School of Mechanical Engineering. Therefore, the same alloy (AA6061) with 3mm thickness was used. The aluminium alloy was chosen to fulfil the TWBs method that used aluminium in automotive industries. The quality and performance of the welded strips were conducted using Universal Testing Machine (UTM), hardness machine and surface roughness machine to measure strength, hardness and roughness of the surface respectively.

CHAPTER 2

LITERATURE REVIEW

2.0 Overview

This chapter is to further explore the FSW relevant research made recently. This section also as a guideline to this research.

2.1 Friction Stir Welding (FSW)

The paper focus on the relatively new joining technology Friction stir welding FSW. Like all friction welding variants, the FSW process is carried out in the solid-phase. Generically solid-phase welding is one of the oldest forms of metallurgical joining processes known to man. Friction stir welding is a continuous hot shear autogenous process involving a non-consumable rotating probe of harder material than the substrate itself. In addition, FSW produces solid-phase, low distortion, good appearance welds at relatively low cost. Essentially, a portion of a specially shaped rotating tool is plunged between the abutting faces of the joint. Once entered the weld, relative motion between the rotating tool and the substrate generates frictional heat that creates a plasticised region around the immersed portion of the tool. The contacting surface of the shouldered region of the tool and the workpiece top contacting surface also generates frictional heat. The shouldered region provides additional friction treatment to the weld region as well as preventing plasticised material being expelled. The tool is then translated with respect to the workpiece along the joint line, with the plasticised material coalescing behind the tool to form a solid-phase joint as the tool moves forward. Although the workpiece does heat up during FSW, the temperature does not reach the melting point. Friction stir welding can be used to join most aluminium alloys, and surface oxide presents no difficulty to the process. Trials undertaken up to the present time show that a number of lightweight materials suitable for the automotive, rail, marine, and aerospace transportation industries can be fabricated by FSW. [2].

In the [3] a model is developed to obtain the friction stir welding (FSW) induced stress in structures, which includes the welding process and the cooling process. The characteristics of the welding stress are presented in the analytical results. A detailed numerical simulation is also performed to verify the effectiveness of the proposed model. Numerical results of the welding stress agree well with the welding stress obtained from the analytical model. Then, the effects of process parameters of FSW on the welding stress are studied by using the analytical model. The process parameters involve the depression depth of the welding tool, the rotational speed, and the advancing speed. The calculated results show that the radial stress in the welded structure decreases with the increase of the depression depth. Larger tensile stress appears beneath the tool shoulder with the increase of the rotational speed. Higher advancing speed introduces lower tensile stress in the welded structure.

2.2 FSW Parameters

Two rectangular plates with dimensions of 1000×150×6.8mm are selected to perform the experiments of FSW. The material of the plate is 2024-T3 aluminium alloy. The test specimen and the welding equipment are shown in Figure 2.1. The radii of the shoulder and the tool pin are 10 mm and 3 mm, respectively. The welding conditions are summarized in Table 2.1. The parameters involved in the welding stress model are measured from the welding experiments. The moment and the axial force of the spindle are obtained from the welding equipment, as given in Table 2.2. The temperature in the welding process is measured by a thermal infrared imager FLIR A615. The measurement accuracy is ±2 °C. The temperature is recorded from the tool starting to move forward along the weld to the end of the welding process.[3]

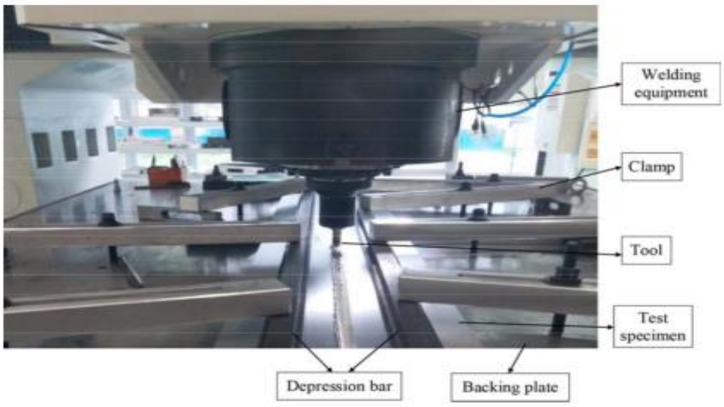


Figure 2.1: FSW main component[3]

Table 2.1: Welding process parameters[4]

Conditions	Dimensions			w/rpm	v/mm min^{-1}	t_p/mm
	L/mm	W/mm	t_0/mm			
1	1000	300	6.8	300	100	0.1
2	1000	300	6.8	300	300	0.1
3	1000	300	6.8	300	500	0.1
4	1000	300	6.8	600	300	0.1
5	1000	300	6.8	300	300	0.2

Table 2.2: Parameters obtained from welding experiments[4]

Parameters	1	2	3	4	5
M/N m	17.20	18.80	20.20	11.00	21.40
P_z/N	−1876	−1970	−2019	−1781	−3230
T_{r1}/°C	243.42	201.93	188.35	229.7	195.31
T_{r2}/°C	140.19	116.78	99.56	131.16	110.20

From the literature [4], the tool geometry, welding parameters, joint designs are the significant parameters affecting the material flow pattern and temperature distribution, thereby influencing the micro structural evolution of the material. The detailed list of FSW process parameters are given below:

1. Rotational speed of the tool (rpm).

2. Welding speed or transverse speed (mm/min).

3. Tool geometry.

(a) Pin profile.

(b) Tool shoulder diameter, D (mm).

(c) Pin diameter, d (mm).

(d) D/d ratio of tool.

(e) Pin length (mm).

(f) Tool inclination angle

The friction stir welding process parameters such as tool rotational speed, transverse speed, and tool geometry significantly influence the process and play a major role in deciding the quality of the weld. It is reported that defect free weld in dissimilar materials of AA5052 to AA2017 are obtained when the transverse speed and rotational speed are at 60 mm/min and 1000 rpm respectively. Further, the rotational speed or welding speed increases the tensile strength to a maximum value and then decreases due the occurrence of void defect. Also, in their studies on friction stir welding of AA8009, found that for the high rotational speed of 1200 rpm the tensile strength value was 60–70% of the base metal and for the lower rotational speed of 428 rpm it was found to be 90%.

2.3 Tool Geometry

Probe or pin is the extended segment of the tool which is inserted into the workpiece by axial force during welding. The movement of tool pin inside the workpiece shears the material ahead of tool and pushes it behind the tool. The main function of the rotating tool pin is to shear the material ahead, provide a stirring action to the plasticized material and move this stirred material behind of the tool for consolidating the joint. Pin profile also governs the welding speed and controls the resulting mechanical properties and joint structure. Important features of tool pin are pin length, pin diameter and surface profile. FSW requires a proper contact between workpiece and shoulder, and it is achieved by maintaining an appropriate axial plunge load along with a shorter pin length of about 0.2−0.3 mm compared to the workpiece. Surface profile and pin diameter have significant effect on material flow pattern, stir zone size and microstructure. ZHAO et al used three different types of tool pin as threaded cylindrical taper cylindrical, and straight cylindrical for dissimilar FSW of Al−Cu and found that taper cylindrical pin provided the highest strength. The end surface of the pin may be flat or domed. Both have their advantages as the flat surface helps to increase the forging force during plunging while domed surface reduces it. The different pin shapes are shown in Figure 2.2.[5]

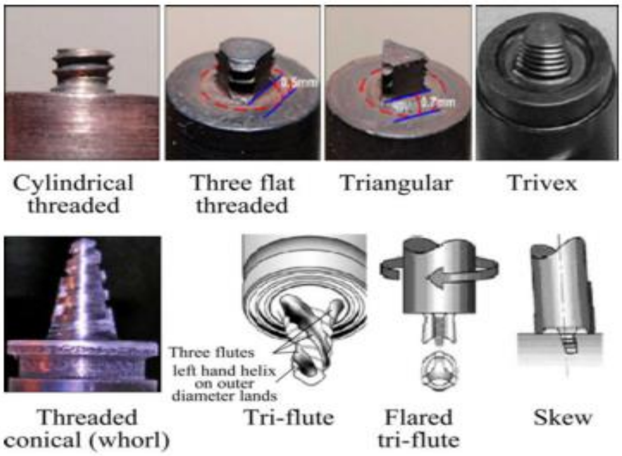


Figure 2.2: Commonly used tool probe shapes[5]

According to [6], the tool threads assist in insuring that the plastically deformed workpiece material is fully delivered around the probe was suggested. Several recent commercial tool designs compared with the conventional cylindrical threaded probe, which have benefits when welding thick plates (thicker than 12mm) and applying higher welding speeds was introduced. To design effective tools for steel, another new concept is necessary. The tool requires all the following characteristics: (a) as simple as shape as possible to reduce the cost; (b) sufficient stirring effect to produce sound welds like an ordinary tool for Al alloys. Three types of Al alloys with different mechanical properties were employed for FSW with the simplest shape in Figure 2.3 (column without threads), ordinary shape (column with threads) and tri- angular prism-shaped probes.

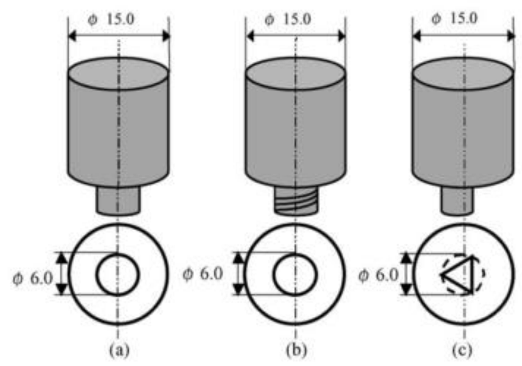


Figure 2.3: FSW Tool Shape: (a) column without threads, (b) column with threads, (c) triangular prism[6]

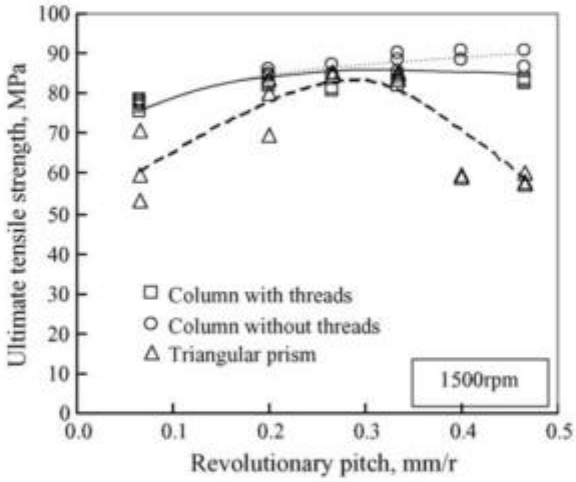


Figure 2.4:Tensile Strength of FSW Joints[6]

From the result, when the revolutionary pitch is equal to or smaller than 0.2 mm/r, the tensile strength using the tool with threads is like that using the tool without threads. However, when the revolutionary pitch is greater than 0.2 mm/r, the tensile strength using the tool without threads is higher than that for the tool with threads. This result can be explained by the welding defects formed in the joints using the tool with threads, as shown in Figure 2.4. For the triangular prism tool, the tensile strength of the joints shows a peak near 400mm/min (the revolutionary pitch is 0.27 mm/r). This result is related to the welding defect distributions in the joints shown in Figure 2.5. Because the defects become small at the welding speed near 400 mm/min, the tensile strength becomes higher than the other speeds, thus forming large defects.

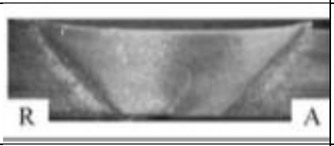
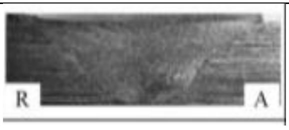
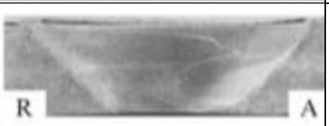
Tool Type	1500rpm, 100mm/min	1500rpm, 400mm/min	1500rpm,700mm/min
Column without threads			
Column with threads			
Triangular prism			

Figure 2.5: Macrostructure of the cross section of FSW joints.[6]

Among the key components of the FSW tool geometry are the tool shoulder and the pin. While the shoulder is the main source of heat generated during the process, the primary constraint to material expulsion and the primary driver for material flow around the tool, the pin is the primary source for material deformation and the secondary source for heat generation in the nugget. Consequently, the geometry of both the shoulder and pin are important to the FSW process. Nugget integrity is therefore primarily dependent on a well-designed pin. for all the pin geometries selected, the same 2.8mm pin height and a 0.5mm fillet radius at the pin–shoulder interface were adopted; different value of the bottom pin diameters (namely d-pin) and of the taper angle were considered for the conical shape; and the shoulder external radius was changed in order to maintain constant con- tact surface between the workpiece and the tool shoulder itself, as shown in Table 2.3 [7].

Table 2.3: Geometrical properties of the tool set utilized[7]

Angle	d_{pin} **(mm)**	$D_{shoulder}$ **(mm)**	**Pin surface area** (mm^2)
0	3.0	10.0	26.3
10	2.5	10.5	31.4
20	2.0	11.0	32.8
30	1.5	11.0	35.8
40	1.0	11.0	43.2

2.4 Clamp Design

According to [8], designed and modified a clamping and support system in a reconfigured milling machine to produce friction stir welding joints. The re-designing of a milling was done to produce friction stir welds. The objective of this design was to develop a clamping and support system for a reconfigured milling machine to be utilized for producing friction stir welds with lesser vibration. They suggested that different thickness plates can be clamped and welded with proposed design. The clamping fixture is design according to the drawing in Figure 2.6. The performance analysis showed that the concept can be used for friction stir welding to be performed by using a typical milling machine. The inexpensive milling machine adaptations allow for the conversion of any milling machine into a specialized Friction Stir Welding machine which is suitable for research purposes.

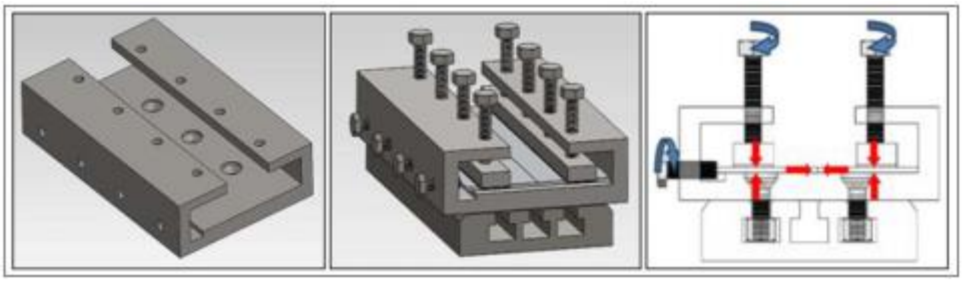


Figure 2.6: Assembly drawing showing the backing plate fastened to the milling machine table and major force involve in a supporting system[8]

Other than that, refer to literature [9][10], only clamping the work piece is not the criteria in FSW, but restriction of movements and flexibility is more important. This type of vice (Figure 2.7) will have size limitations as well as risk of accident. To do the research work one has to experiment as per guidelines laid by standards developed previously, and for that such vice will not serve the purpose. If we clamp using this vice, then there are maximum chances of lifting of substrate from the centre. So proper understanding is required to be developed for proper clamping of the work piece (plates) to be butt welded. The design required for designing clamp is, (i) a rigid clamping is required to get sound weld and to avoid accident during friction stir welding, (ii) a backing plate is required, which will provide strong support sufficient enough to limit bending of substrate, (iii) horizontal and vertical plate movement should be restricted.

Figure 2.7: Vice used in conventional machining process[9]

It is necessary to clamp plates from top to avoid lifting of or bending of plates (Figure 2.8) resulting from clamping done using conventional milling vice. So, it was thought to apply clamping force from the top (Figure 2.9). In this design it provides side clamps along with the upper plates. These side clamps can restrict the side movement of the plates to be welded, and no splitting will occur in butt region.

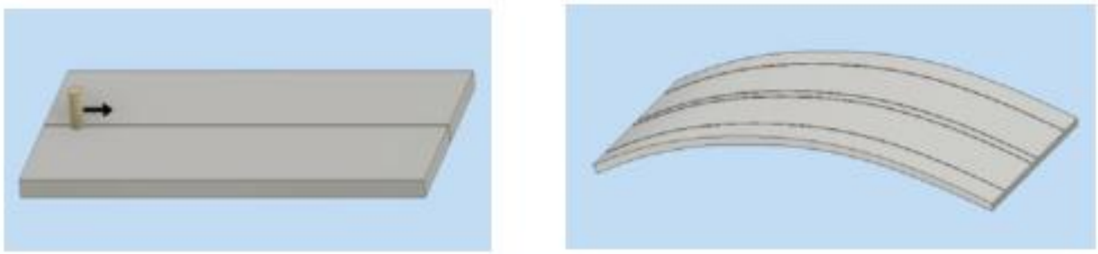


Figure 2.8: Plates without clamping (or clamping in the vice)[9]

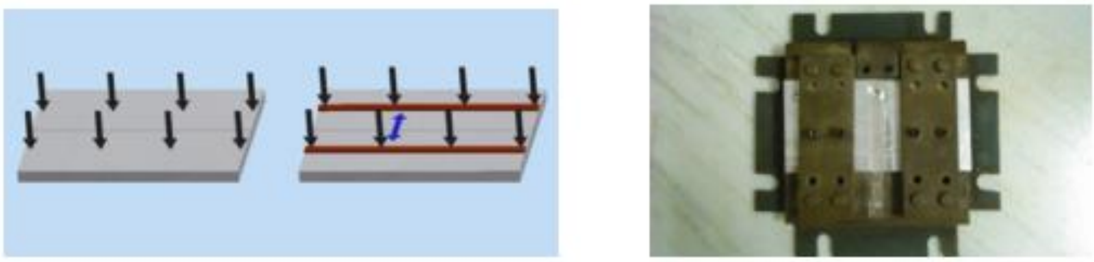


Figure 2.9: Clamping the plates from top[9]

2.5 Tensile Test

In the literature [4], all the three of the welded specimen was failed in 5083-side heat affected zone(HAZ). Alloy 2219 is significantly stronger compared to alloy 5083. The welded specimens showed slightly lower strength compared to 5083 base material specimens. Figure 2.10 shows the typical failed tensile test specimen. Refer to literature [11] ,the tensile strength of welded joint increases with increase in tool rotational speed as illustrated in Figure 2.11. The amount of heat to metal plates will become low if the decrease in rotational speed inputs. The lowered heat supply to the base material will considerably lead to insufficient material flow and followed by a less plasticized stir zone. The reduced tensile strength at lesser rotational speed is consequence of minimal plasticized material that fails to mix properly.

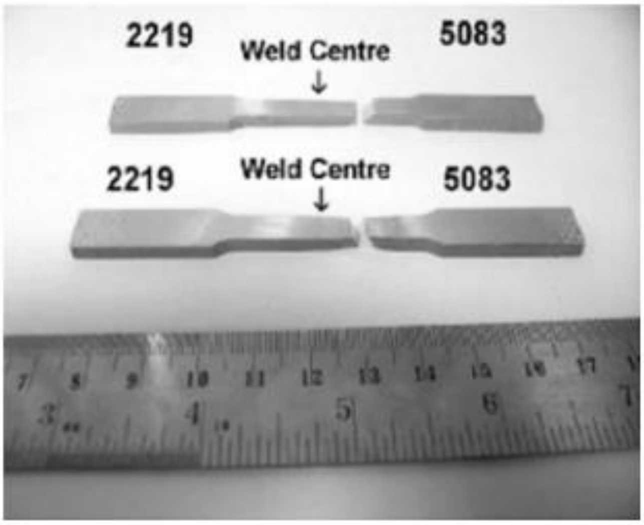


Figure 2.10: Typical failed tensile test specimens.[4]

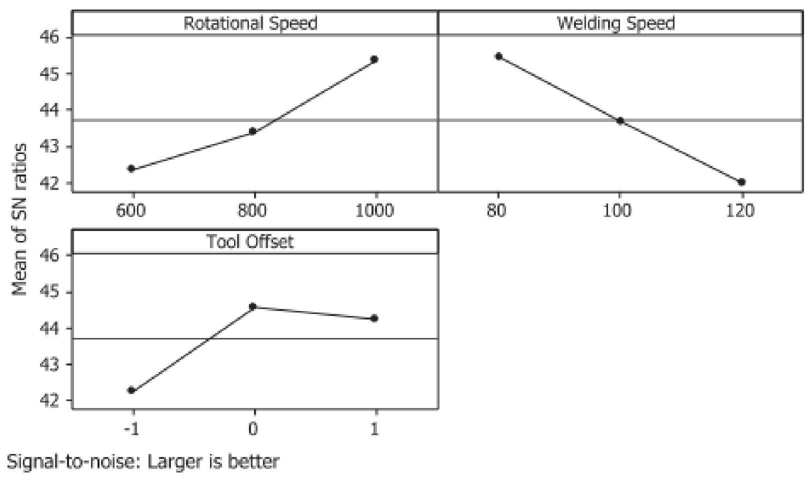


Figure 2.11: Effect of tool rotational speed, welding speed and tool offset on Tensile Test[4]

2.6 Hardness Test

The hardness value of weld joint decreases with increase in rotational speed (Figure 2.12). [11] The larger heat generation at higher tool rotational speed cause more heat dissipate to workpiece resulting in the formation of coarse grain structure at the weld zone. This reduces the hardness of the weld zone[12]. The principle of impact strength is, more the energy absorbed by the material, lesser will be the tendency to get fracture.

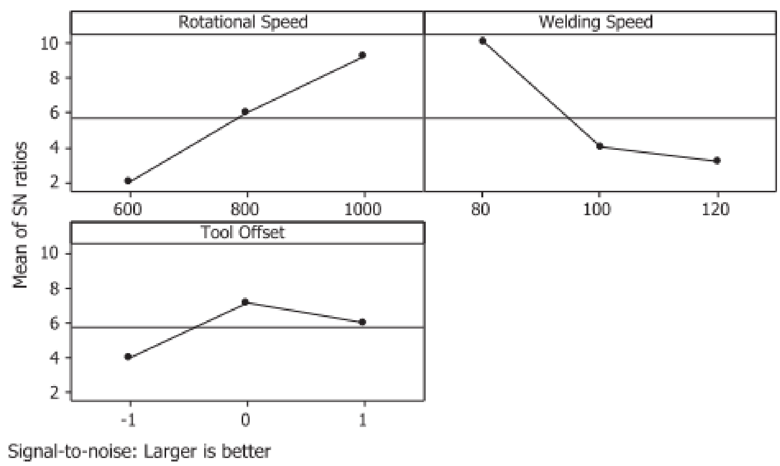


Figure 2.12: Effect of tool rotational speed, welding speed and tool offset on Hardness Test[11]

CHAPTER 3

METHODOLOGY

3.0 Overview

This chapter discuss about the method used to enable friction stir welding and the testing. Its shows the method on designing the fixture and tool and the fabrication of the fixture and tool. This chapter also shows how the friction stir welding experiment run. The testing on the friction stir welding specimen is tensile test, hardness test and roughness test. There is also state the machine involves in designing and running this experiment.

3.1 Design and Fabrication the Fixture (Clamp) and Tool

In this section, the fixture shown in Figure 3.1 and tool shown in Figure 3.2 was designed using SolidWorks software. According to the [13] the design of the fixture should have a key for fixing and balancing the sheet so that the sheet do not get displace from their position while performing FSW. Second things were the design should allow the fixture to properly mount over the conventional milling machine that want to use. After considering the versatile features, the fixture is design according to the size of work table of the milling machine where is the size of the milling machine table was 300mm x 1500mm. The dimension of the backing plate as shown in Figure 3.1(a) is 350mm x 250mm. the width of the baking plate was large than the milling machine table but the design still convenient to used. This is because of the size of the aluminium sheet to be welded where the size is 200mm x 80mm each and need to combine two of the aluminium sheet during the FSW process and become 200mm x 160mm, thus the backing plate must be larger than the specimen. The left and right clamp indicate in Figure 3.1(b) was making to hold the specimen to avoid a gap or left and right movement between the two specimens. The clamp also acts as hold up to avoid the specimen from lifting of or bending during the FSW. The assemble design of the fixture is shown in the Figure 3.1. The fixture was fabricated using milling machine and drilling machine.

The tool is design according to the type and the thickness of the specimen material that want to be weld. For this project, the specimen material Aluminium 6061 then the tool steel is used to fabricate the tool. A cylindrical tool shape was used to fabricate joints of FSW. The tool consists of a shoulder and a pin. From the literature [6][5], there are many type of the pin. For this project, the cylindrical pin without threaded was selected. This is because it is simple to fabricate using conventional milling machine that available in the lab. The height of the pin and shoulder was 2mm and 10mm respectively. The tool was design according to the thickness of the specimen 3mm. The tool was fabricated using bend saw and lathe machine.

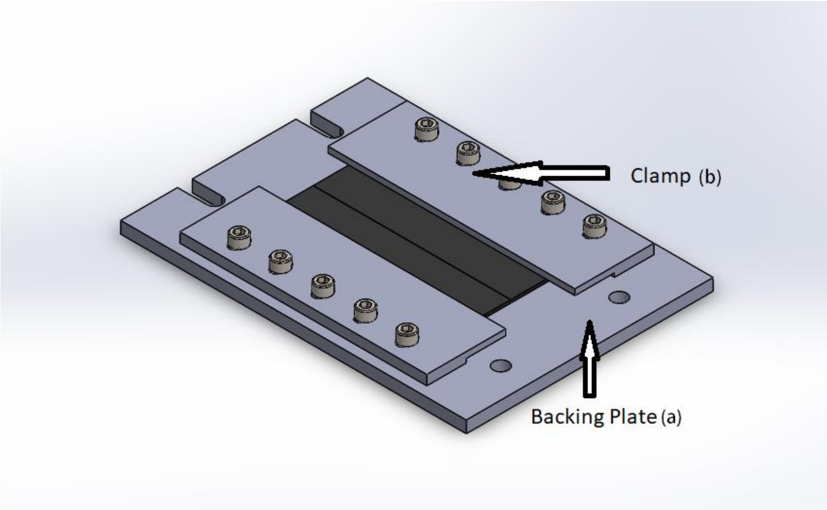


Figure 3.1: Design of the Fixture

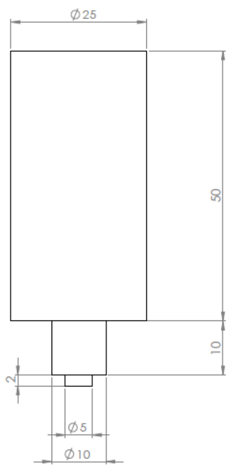


Figure 3.2: Dimension of the Tool (unit in mm)

3.2 Experimental Design

Butt-welding of A6061 aluminium alloys was performed. The sheet is 3mm thick, 80mm wide and 200mm long. In this study, the conventional milling machine (Figure 3.4) was used to enable friction stir welding. The feed rate available on this machine is from 11mm/min to 500mm/min and the spindle speed lies between 48rpm to 1500rpm. The tool profiles are showed in Figure 3.2. A tool with a columnar pin without threads was used in the experiment. The total length pin and the diameter and length of the shoulder is 10mm and 5mm respectively. The aluminium sheets to be friction stir welded were clamped on the backing plate which was bolted directly to the bed of the milling machine. The spindle of the conventional milling machine was tilt to curtain angle. The feed rate (welding speeds) and the spindle speed (rotational speed) were achieved using the control system and the panel. The welding parameters such as spindle speed (rotational speed), feed rates (welding speeds), and tilt angle was tabulated in Table 3.1.

Table 3.1: Experiment parameters using Taguchi Method using Minitab

SPECIMEN NO	ANGLE (°)	SPINDLE SPEED (rpm)	FEED RATE (mm/min)
S1	2	600	31
S2	2	865	65
S3	2	1140	90
S4	3	600	65
S5	3	865	90
S6	3	1140	31
S7	4	600	90
S8	4	865	31
S9	4	1140	65

The parameters of this experiment were obtained from Taguchi Method. The most important difference between a classical experimental design and a Taguchi-method-based robust design technique is that the former tends to focus solely on the mean of the quality characteristic while the later considers the minimization of the variance of the characteristic of interest. The Taguchi method attempts to optimize a process or product design consists of three stages, as follows:

i. Concept design or system design.
ii. Parameter design.
iii. Tolerance design.

The following are the steps to be followed for process parameter optimization. First, the quality characteristic to be optimized was determined. Then, the noise factors and test conditions and the control factors and their alternative level was identified. Next, design the matrix experiment and define the data analysis procedure and conduct the matrix experiment. The next step was analysing the data and determine optimum levels for control factors and last predict the performance at these levels. This Taguchi Method was obtain using the Minitab Software. As three levels and three factors are taken into consideration, L9 Orthogonal arrays as in Table 3.2 is used in this investigation. Only the main factor effects are taken into consideration and not the interactions. The result of Taguchi method was obtained on Table 3.1.[14]

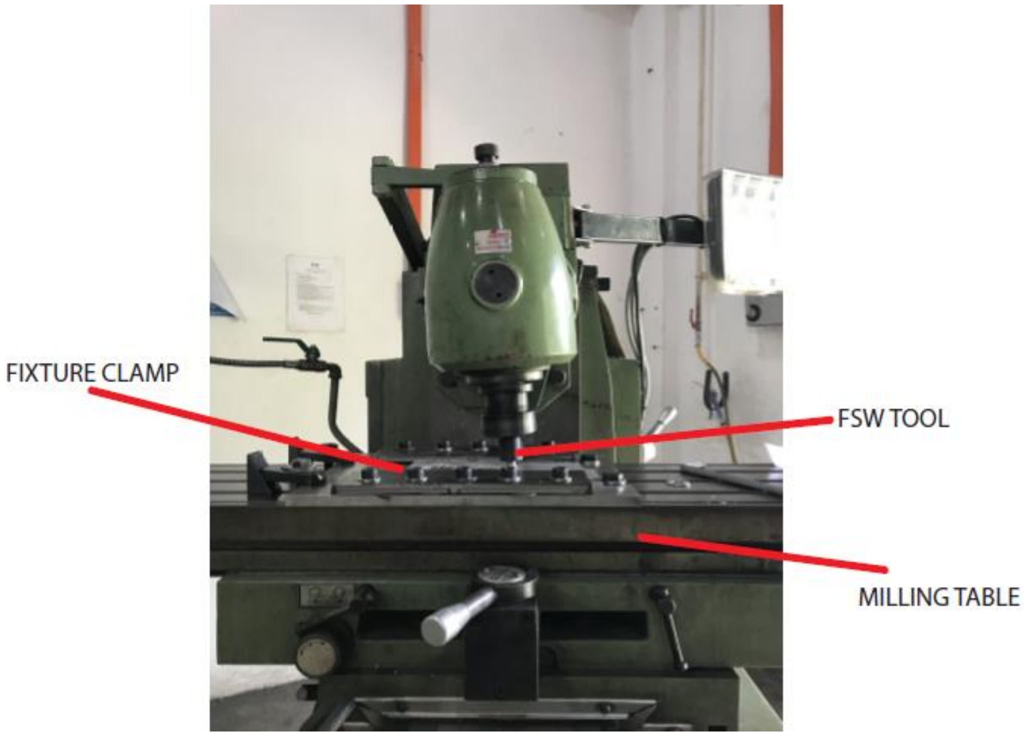


Figure 3.3: Conventional Milling Machine

Table 3.2: Taguchi Orthogonal Arrays L9

Run	Columns			
	1	2	3	4
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

3.3 Tensile Test

Tensile specimens with the total length of 100mm, a gage length of 25mm and a width of 6mm were prepared from the welded specimen. The wire cut EDM was used to cut the smooth profile tensile specimens. The tensile specimens were cut perpendicular to welded joint and tensile tests were conducted on nine samples as per ASTM E8[15] on a universal tensile testing machine that show in Figure 3.4. The dimensions of tensile specimen are shown in Figure 3.5. In each welded joint, five tensile specimens were cut for testing and the tensile strength is obtained by averaging the five values. The total tensile specimen was 50 pieces included the base material (AA6061). The prepared tensile specimens were subjected to tensile test and their ultimate tensile strengths were evaluated.

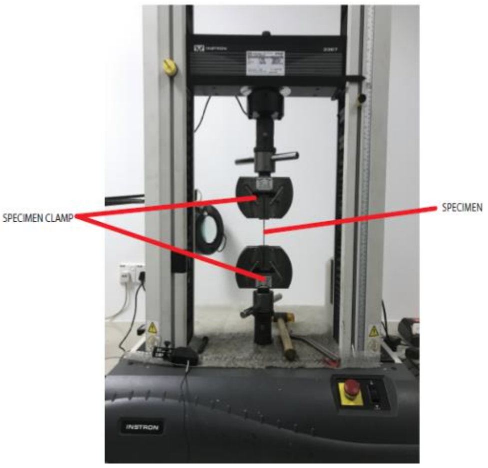


Figure 3.4: Universal Tensile Testing Machine (UTM)

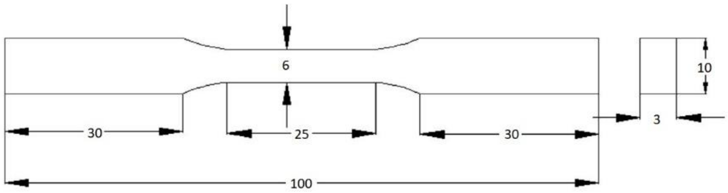


Figure 3.5: Dimensions of tensile specimen (unit in mm)

3.4 Hardness Test

In this hardness test, there is two methods of taking measurement in this experiment. The first method is to measure hardness along the weld line as shown in Figure 3.6. This is to determine the highest hardness among the nine specimens. The second method is, to measure the hardness perpendicular to the welded line as shown in Figure 3.7 This method is to determine the hardness from the centre of the weld line to the outer base materials. The purpose of this second method is to determine the hardness different between the weld zone and the base material. In this experiment, the Rockwell harness as shown in Figure 3.9 tester was used to determine the hardness. Steel ball with diameter 1.588mm and 100kg of load is used for the Rockwell test in this experiment. The parameter was taken from [14-15] as a references.

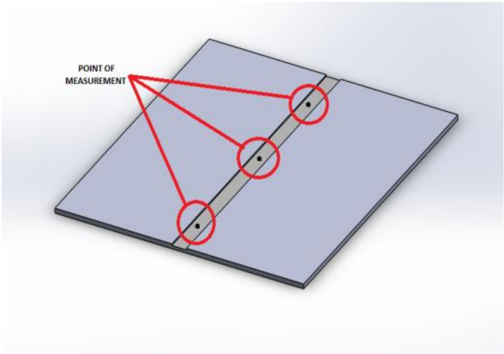


Figure 3.6: Hardness test along the weld line

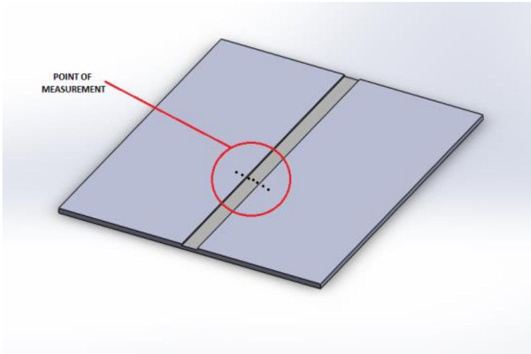


Figure 3.7: Hardness test perpendicular to weld line

3.5 Roughness Test

The roughness test was performed at the weld area and the test were conducted in the Metrology Laboratory by using roughness tester as shown in Figure 3.8. The range of roughness was set to 400 μm and the distance 4mm. the roughness was carried out in 3 points (left-middle-right) on the welding line.

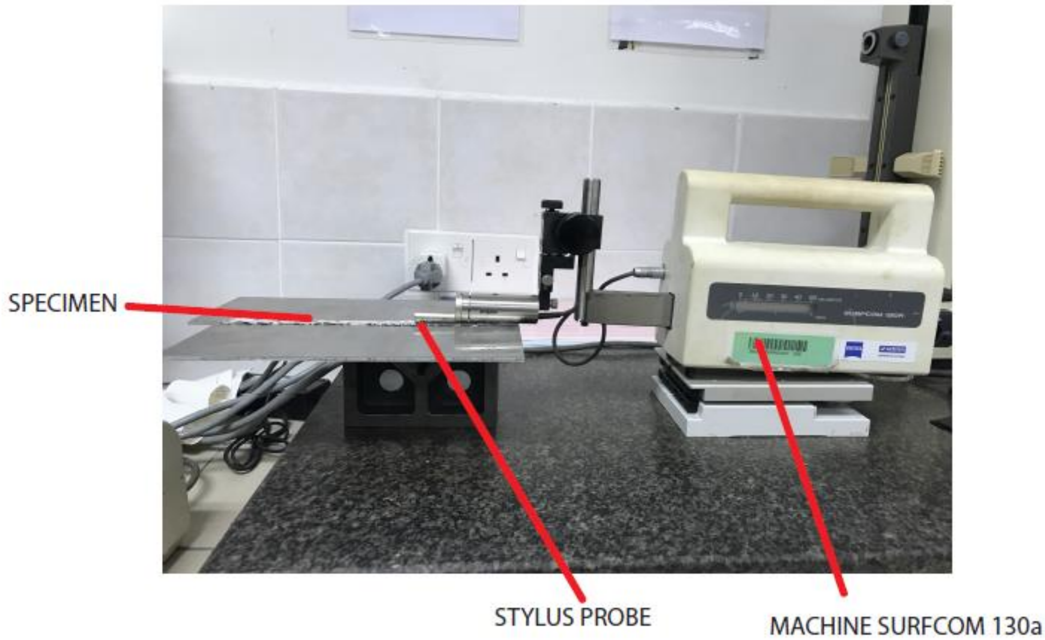


Figure 3.8: Roughness Tester Surfcom 130a

CHAPTER 4

RESULT AND DISCUSSION

4.0 Overview

This chapter discuss the testing result of the friction stir welding specimen. First section discusses about the tensile test to determine the maximum tensile strength and to get the stress and strain curve. The second test is hardness test using Rockwell hardness tester to get the hardness value along the welding line and the hardness perpendicular to weld line. The final test is roughness test to determine the best surface finish that can be obtained from all the parameters tested.

4.1 Tensile Test

The tensile test was conducted to get the tensile strength and stress-strain curve. The tensile specimen before and after is shown in Figure 4.1. Stress strain curve were constructed shown in Figure 4.2 and Table 4.1 is to compare relationship between engineering stress and engineering strain of Aluminium 6061 base material and all the nine sets of specimens after welding process. From the graph, the stress-strain curve for the base materials is higher than the FSW specimen. This is because, after going through the FSW process the thickness of the material will reduce and as a result the maximum stress for the FSW process lowest from the base material. The graph reveals that S6 results in the highest stress-strain curve with 175.28 MPa stress value while S3 results in lowest stress value which is 129.09 MPa. S6 is the combination of parameter 3° tool angle 1140 rpm spindle speed and 31 mm/min feed rate proved that high spindle speed and lower the feed rate will produce sufficient heat to make sure both material well combined as compared to S3, a combination of parameter 2° tool angle 1140 rpm spindle speed and 90 mm/min feed rate which also use high spindle speed but use highest feed rate.

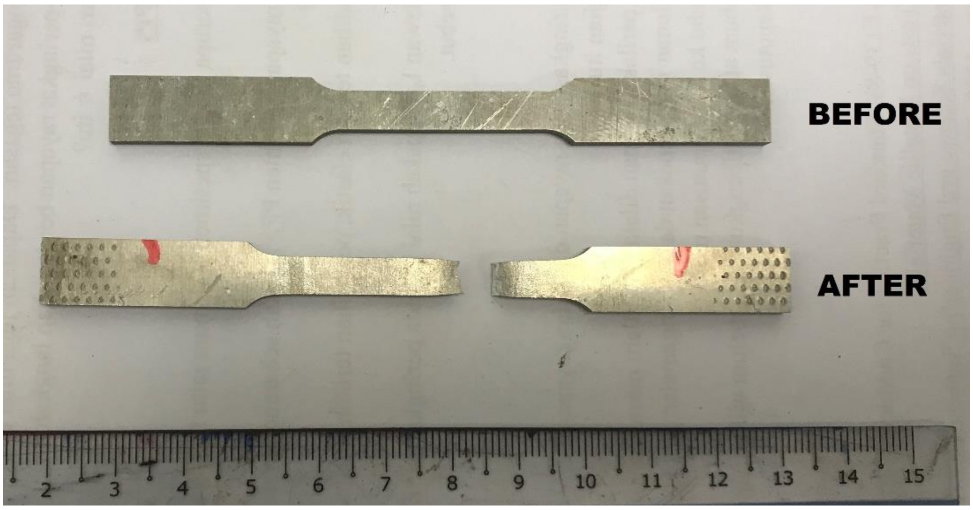


Figure 4.1: Tensile specimen before and after

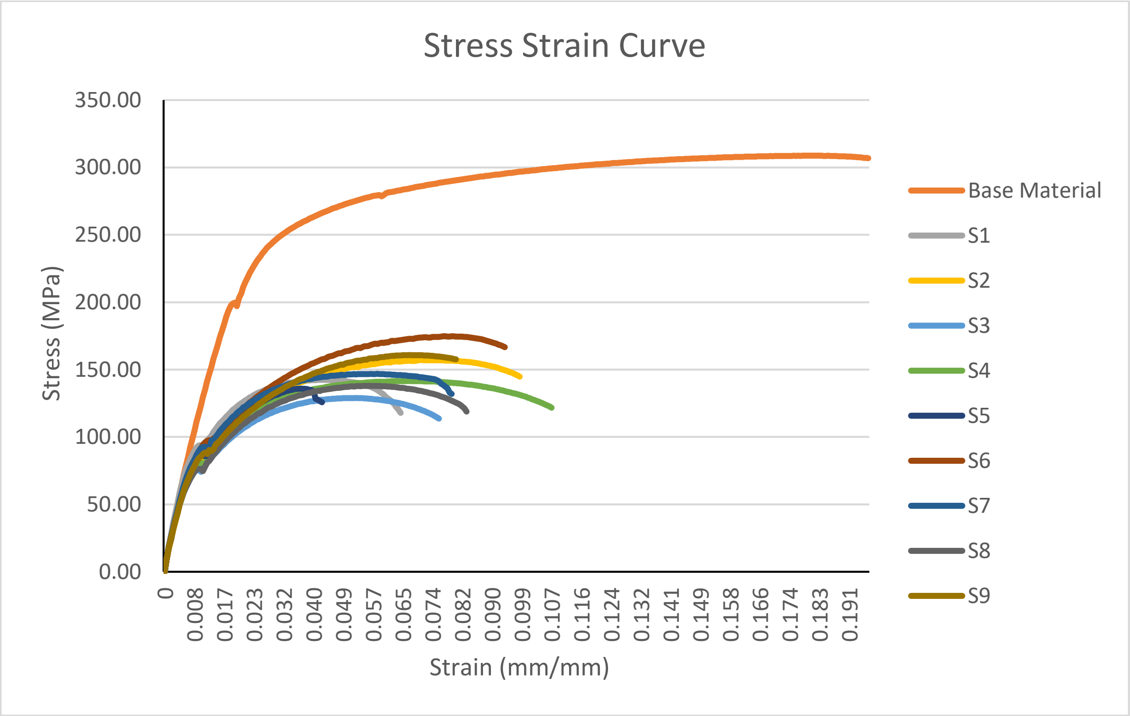


Figure 4.2: Stress-Strain Curve

Table 4.1 : Result on Tensile Strength (MPa)

Specimen No.	Tool Angle	Spindle Speed (rpm)	Feed Rate (mm/s)	Tensile Strength (MPa)
S1	2	600	31	142.669
S2		865	65	169.3974
S3		1140	90	129.0912
S4	3	600	65	141.6952
S5		865	90	136.9676
S6		1140	31	175.2846
S7	4	600	90	146.9868
S8		865	31	138.1266
S9		1140	65	160.9678

After the orthogonal arrays was implement, the main effects for mean and SN ratio of the process parameters on tensile strength is plotted in Figure 4.3 and Figure 4.4. It shows the best and the optimize parameters in this experiment. The tensile strength of welded joint increases with the increase in spindle speed (rotational speed) as shown in Figure 4.4. The heat generation due to friction is mainly dependent on the spindle speed (rotational speed). Lower spindle speed but high feed rates will produce insufficient heat due to lower friction that will produce poor plastic flow and formation of defects in welded zone. Therefore, higher in spindle speed (rotational speed) and lower the feed rate (welding speed) will produce sufficient heat to make sure both of the material well combined and will resulting in the formation of coarse grain structure at the weld zone [18].

The tensile strength increase start from 31mm/min up to 65mm/min but start to decrease from 65mm/min to 90mm/min. This is because when the welding speed too fast, the melting material cannot mix properly and did not have enough time to combine. This is the reason for weak interface at the joint [12]. When the welding speed is greater

than 65mm/min a crack-like defect is more easily formed in the joint that will affected the tensile strength[6]. For the tool angle, 3° angle is the optimize angle that can be